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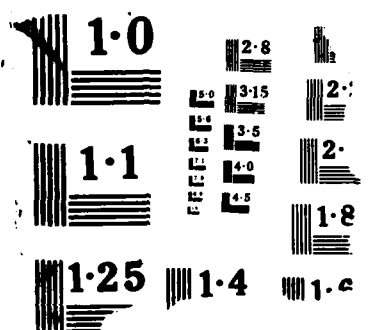
PREDICTING PRODUCT WATER QUALITY FROM THE  
600-GALLON-PER-HOUR REVERSE OSM. (U) COLD REGIONS  
RESEARCH AND ENGINEERING LAB HANOVER NH J R BOUZOUN  
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# Special Report 88-2

February 1988



**US Army Corps  
of Engineers**

Cold Regions Research &  
Engineering Laboratory

AD-A194 988

## *Predicting product water quality from the 600-gallon-per-hour reverse osmosis water purification unit*

*Field water supply on the winter battlefield*

John R. Bouzoun

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Prepared for  
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SECURITY CLASSIFICATION OF THIS PAGE

ADA 194988

## REPORT DOCUMENTATION PAGE

Form Approved  
OMB No 0704-0188  
Exp Date Jun 30, 1986

1a REPORT SECURITY CLASSIFICATION <b>Unclassified</b>			1b RESTRICTIVE MARKINGS		
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.		
2b DECLASSIFICATION/DOWNGRADING SCHEDULE					
4 PERFORMING ORGANIZATION REPORT NUMBER(S) <b>Special Report 88-2</b>			5 MONITORING ORGANIZATION REPORT NUMBER(S)		
6a NAME OF PERFORMING ORGANIZATION <b>U.S. Army Cold Regions Research and Engineering Laboratory</b>		6b OFFICE SYMBOL (If applicable) <b>CECRL</b>	7a NAME OF MONITORING ORGANIZATION <b>Office of the Chief of Engineers</b>		
6c ADDRESS (City, State, and ZIP Code) <b>72 Lyme Road Hanover, New Hampshire 03755-1290</b>			7b ADDRESS (City, State, and ZIP Code) <b>Washington, D.C. 20314</b>		
8a NAME OF FUNDING/SPONSORING ORGANIZATION		8b OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
PROGRAM ELEMENT NO. <b>6.27.30A</b>		PROJECT NO <b>4A7627 30AT42</b>	TASK NO <b>CSS</b>	WORK UNIT ACCESSION NO <b>001</b>	
11. TITLE (Include Security Classification) <b>Predicting Product Water Quality from the 600-Gallon-Per-Hour Reverse Osmosis Water Purification Unit. Field Water Supply on the Winter Battlefield.</b>					
12. PERSONAL AUTHOR(S) <b>Bouzoun, John R.</b>					
13a. TYPE OF REPORT		13b TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) <b>February 1988</b>	
15 PAGE COUNT <b>14</b>					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Drinking water; Water purification; Reverse osmosis; Water quality; potable water		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) A preliminary equation for predicting the total dissolved solids (TDS) concentration in the product water from the 600-gph ROWPU is presented. The equation requires the raw water temperature and TDS concentration as input data. Both of these variables can be easily measured in the field. The equation is presently limited to raw water TDS concentrations in the range of 800-900 mg/L. As data become available for a greater range of raw water TDS concentrations, including seawater, the equation will be modified. The standard error of the estimate is 3.4 mg/L. <i>Reported</i>					
20 DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION <b>Unclassified</b>		
22a NAME OF RESPONSIBLE INDIVIDUAL <b>John R. Bouzoun</b>			22b TELEPHONE (Include Area Code) <b>(603) 646-4100</b>		22c OFFICE SYMBOL <b>CECRL-EA</b>

## **PREFACE**

This report was prepared by John Bouzoun, Research Environmental Engineer, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this report was provided by DA Project 4A762730AT42, *Design, Construction and Operations Technology for Cold Regions*, Mission Area, *Combat Service Support*, Work Unit 001, *Field Water Supply on the Winter Battlefield*.

Dr. C. James Martel and Robert Sletten of CRREL technically reviewed the manuscript of this report.

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**CONVERSION FACTORS: U.S. CUSTOMARY TO  
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These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E380).

Multiply	By	To obtain
degrees Fahrenheit	$t_{\circ C} = (t_{\circ F} - 32)/1.8$	degrees Celsius
feet	0.3048*	meters
gallons	0.003785412	cubic meters
pounds	0.4535924	kilograms

\*Exact

# Predicting Product Water Quality from the 600-Gallon-Per-Hour Reverse Osmosis Water Purification Unit

## Field Water Supply on the Winter Battlefield

JOHN R. BOUZOUN

### INTRODUCTION

In March 1974 the Army officially stated its need for a water purification unit that was capable of purifying most of the raw waters encountered in the field, including seawater. As a result, the 600 gallon-per-hour (gph) Reverse Osmosis Water Purification Unit (ROWPU) was accepted for use by the Army in June 1979.

The 600-gph ROWPU is a trailer-mounted mobile water purification unit. Power for the unit is supplied by a 30-kW diesel generator that is also mounted on the trailer. The entire unit is approximately 19 feet long and 8 feet wide and high, and weighs 17,000 pounds. The ROWPU has three water treatment processes in series that remove the suspended and dissolved solids from the raw water. They are the multimedia filter, the cartridge filter, and the reverse osmosis vessels.

The multimedia filter consists of six layers of synthetic pellets, anthracite, sand and gravel contained in a steel tank. A polymer is added to the raw water to cause small suspended particles to flocculate together into larger particles, which are removed by the multimedia filter. The cartridge filter consists of eight woven polypropylene filters with 5- $\mu$ m openings. The cartridge filter removes the very small particles that are left in the water coming from the multimedia filter. Then the water passes through the four reverse osmosis pressure vessels, each with two spiral-wound polyether-urea reverse osmosis elements. Each of these eight elements has 159 ft<sup>2</sup> of surface area, giving a total surface area of 1272 ft<sup>2</sup>. As the water passes through these elements, the dissolved solids are removed by a membrane separation process.

The reverse osmosis process is illustrated in Figure 1. Figure 1a shows a container divided in half by a semipermeable membrane, with a known volume of clean water in the left half and the same volume of a salt water solution in the right half. The clean water from the left half will flow through the membrane into the right half, attempting to equalize the salt concentration, while the membrane prevents the flow of salt in the opposite direction, as shown in Figure 1b. If pressure is applied to the right side (Fig. 1c), the flow of water from the left side can be reduced and even stopped. The pressure at which the flow is stopped is called the osmotic pressure of the salt solution. If the pressure is increased above the osmotic pressure of the salt solution (Fig. 1d), the water flows into the left side of the container, leaving the salts in the right half of the container. This is called reverse osmosis.

The purpose of this report is to present the analytical procedure used to develop a preliminary equation to predict the total dissolved solids (TDS) concentration in the product water from the Army's 600-gph ROWPU. The equation presented here is based on a narrow range of raw water TDS concentrations (800-900 mg/L) and therefore should be considered preliminary. After additional data have been collected and analyzed, the equation will be modified. The equation is simple to use and only requires the raw water temperature and the raw water TDS as input data.



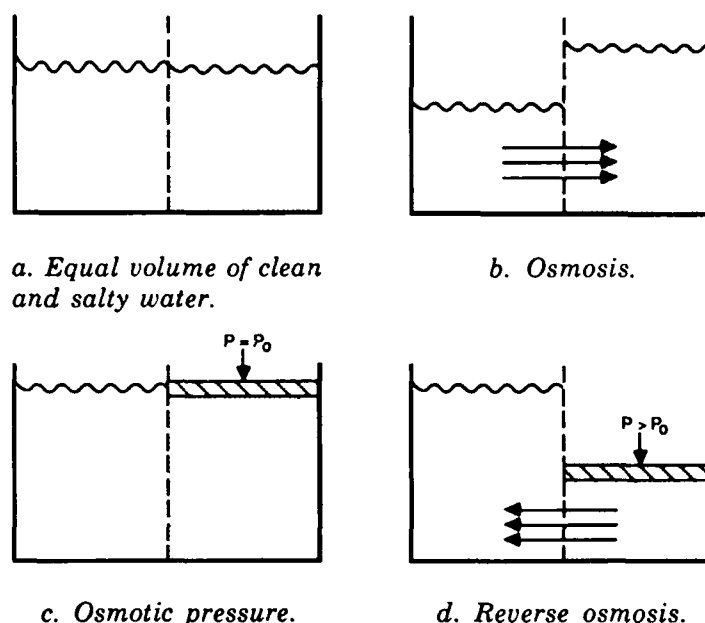


Figure 1. Principle of reverse osmosis.

Both of these parameters can be measured by the water purification specialist in the field using the TDS meter and the thermometer that come with the ROWPU.

The final result of this project, after further testing and modification of the equation, will be a simple table of product water TDS concentrations at different raw water temperatures and TDS concentrations. This table will be submitted as a suggested change to the 600-gph ROWPU Technical Manual (U.S. Army 1982) and to the Army Field Manual on Field Water Supply (U.S. Army 1985). This information will be of value to water supply specialists, commanders and staff officers, particularly in selecting raw water sources if more than one exists in their area of operations.

#### TOTAL DISSOLVED SOLIDS FLUX

The flux of salt (TDS) through a reverse osmosis element is directly proportional to the difference between the raw water and the product water salt concentrations. It can be expressed mathematically by the following equation (Lindsten 1986)

$$S = K_2(C_r - C_p) \quad (1)$$

where

- $S$  = salt flux (g/hr per ft<sup>2</sup> of membrane)
- $C_r$  = salt concentration in the raw water (mg/L)
- $C_p$  = salt concentration in the product water (mg/L)
- $K_2$  = proportionality constant (L/hr per ft<sup>2</sup> of membrane).

Another equation that expresses  $S$  as a function of product water TDS concentration is

$$S = Q_{pf} C_p \quad (2)$$

where  $Q_{pf}$  is the product water flux (L/hr per ft<sup>2</sup> of membrane).

### SALT CONCENTRATION EQUATION

Both eq 1 and 2 give the salt flux rate. Because they both equal  $S$ , they may be set equal to each other:

$$K_2(C_r - C_p) = Q_{pf} C_p \quad (3)$$

Equation 3 can be solved for  $C_p$  to give the following equation:

$$C_p = K_2 C_r / (Q_{pf} + K_2) \quad (4)$$

Equation 4 gives the TDS concentration of the product water from the 600-gph ROWPU in terms of three parameters. The TDS concentration of the raw water,  $C_r$ , can be measured in the field using the TDS meter issued with the ROWPU. The proportionality constant  $K_2$  and the product water flow rate  $Q_p$  remain to be calculated.

### THE PROPORTIONALITY CONSTANT

If eq 1 is solved for  $K_2$ , the proportionality constant, we get

$$K_2 = S / (C_r - C_p) \quad (5)$$

This means that we have to know the salt flux rate  $S$ , the TDS concentration in the raw water  $C_r$ , and the TDS concentration in the product water  $C_p$ . It would also be beneficial if these data were available at different raw water temperatures so its effect on the proportionality constant could be determined. Fortunately these data do exist from previous work to determine the effects of raw water temperature on the production rates of the ROWPU (Bouzoun et al. 1986). Table 1 gives these data.

**Table 1. Water quality and quantity data.**

Average raw water temp (°F)	Measured product water flow (gal./hr)	TDS (mg/L)	
		Raw water	Product water
33.7	348	800	42
37.9	407	800	43
42.1	430	800	41
46.8	444	900	43
51.5	459	800	47
57.8	600	800	53
68.3	687	900	60

**Table 2. Salt flux rates.**

Average raw water temp (°F)	Salt flux (g/ft <sup>2</sup> hr)
33.7	0.0435
37.9	0.0521
42.1	0.0525
46.8	0.0568
51.5	0.0642
57.8	0.0946
68.3	0.1227

These data can be entered into eq 2 to determine the salt flux rate in the product water at the various raw water temperatures. For example, at 33.7°F, eq 2 would give the following

$$S = (42 \text{ mg/L}) \times (3.785 \text{ L/gal.}) \times (\text{g}/1000 \text{ mg}) \times (348 \text{ gal./hr}) \times (1/1272 \text{ ft}^2) \\ = 0.0435 \text{ g/ft}^2 \text{ hr.}$$

The 1272 ft<sup>2</sup> in this calculation is the area of the reverse osmosis element in the 600-gph ROWPU. Table 2 gives the calculated salt flux rates at the various raw water temperatures.

Now that the salt flux rates have been calculated, the concentration of salts in the raw water and in the product water from Table 1 can be used in eq 5 to calculate  $K_2$  at the various raw water temperatures. For example at 33.7°F, we get

$$K_2 = (0.0435 \text{ g/ft}^2 \text{ hr} \times 10^3 \text{ mg/g}) / (800 \text{ mg/L} - 42 \text{ mg/L}) \\ = 0.0574 \text{ L/ft}^2 \text{ hr.}$$

Now that we have the proportionality constants at seven raw water temperatures Table 3), we need to develop an equation that will predict the proportionality constant at any temperature within the range of the temperatures of the experimental data. This is done by performing a regression analysis of the proportionality constant as a function of their respective raw water temperatures. In this case, if we do the regression analysis of the natural logarithms of the proportionality constants as a function of the raw water temperatures, we get the following equation:

$$K_2 = 0.0216e^{0.0281T} \quad r = 0.95 \quad (6)$$

where  $e$  is the base of the natural logarithms (2.7183) and  $T$  is the raw water temperature (°F).

Figure 2 is a plot of the calculated proportionality constants and the line of best fit as given by eq 6. Table 3 gives both the calculated and the predicted proportionality constants at the different raw water temperatures.

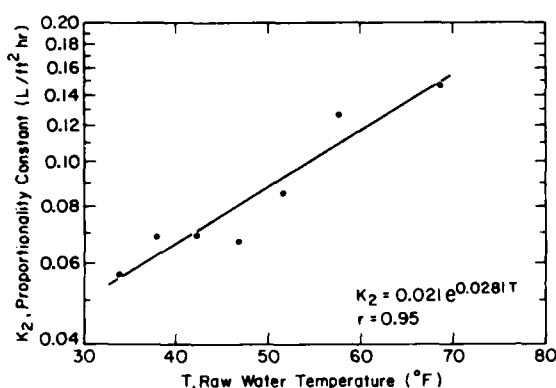


Figure 2. Proportionality constants as a function of raw water temperature.

Table 3. Calculated and predicted proportionality constants.

Average raw water temp (°F)	Proportionality constant (L/ft <sup>2</sup> hr)	
	Calculated	Predicted
33.7	0.0574	0.0555
37.9	0.0688	0.0625
42.1	0.0692	0.0703
46.8	0.0663	0.0802
51.5	0.0853	0.0915
57.8	0.1266	0.1092
68.3	0.1461	0.1466

In addition to visually comparing the calculated and the predicted values of the proportionality constants, we can determine how valid the correlation coefficient  $r$  is under different conditions.

We know that a value of  $r$  close to one (1) indicates a high positive correlation between the two sets of data; a value of  $r$  close to zero (0) indicates that the two sets of data are not related. Because our regression has resulted in an  $r$  value of 0.95, we can say that there is a high positive correlation between the proportionality constant and the raw water temperature. (However, this does not imply a cause-and-effect relationship between them.) To determine how valid the correlation is between raw water temperature and the proportionality constant, we test the null hypothesis,  $H_0 : r = 0$ , against the alternative hypothesis,  $H_1 : r \neq 0$ . To do this we calculate a  $t$ -statistic using the formula

$$t = \sqrt{vr^2/(1-r^2)}$$

where  $v$  is the degrees of freedom ( $n - 2$ ) and  $n$  is the number of data pairs. Then

$$t = \sqrt{5(0.95)^2/(1-0.95^2)} = \pm 6.803.$$

The 95% confidence interval for the  $t$ -statistic with five degrees of freedom is  $\pm 2.571$ . Since the  $t$ -statistic we calculated ( $\pm 6.803$ ) falls outside of this range, we reject the null hypothesis that  $r = 0$ , accept the alternative hypothesis that  $r \neq 0$ , and conclude that  $r$  is highly significant.

## PRODUCT WATER FLOW

In addition to the proportionality constant and the raw water TDS concentration, it is necessary to know the product water flow rate before we can use eq 5 to predict the TDS concentration in the product water. Bouzoun et al. (1986) developed an equation to predict product water flow as a function of raw water temperature:

$$Q_p = 188.3e^{0.019T} \quad (7)$$

where  $Q_p$  is product water flow (gal./hr) and  $T$  is raw water temperature ( $^{\circ}\text{F}$ ).

Equation 7 gives the product water flow in terms of gallons per hour. To convert the product water flow to liters per hour, we multiply it by 3.785, the number of liters per gallon. Then, using the identity  $Q_{pf} = Q_p/A$ , where  $A$  is the total area of reverse osmosis membrane in the 600-gph ROWPU (1272 ft<sup>2</sup>), we divide eq 7 by 1272 to get

$$Q_{pf} = 0.560e^{0.019T}. \quad (8)$$

## OVERALL PRODUCT WATER TDS CONCENTRATION

Now we have equations to predict the proportionality constant and the product water flow, both as functions of the raw water temperature. The only other input parameter required by eq 4 is the raw water TDS concentration, which can be measured in the field using the TDS meter that comes with the ROWPU.

If we substitute eq 6 and 8 for their appropriate symbols in eq 4, we get the following equation:

$$C_p = 0.0216 e^{0.0281T} C_r / (0.560 e^{0.019T} + 0.0216 e^{0.0281T}) \quad (9)$$

where

$C_p$  = TDS concentration in the product water (mg/L)  
 $C_r$  = TDS concentration in the raw water (mg/L)  
 $T$  = raw water temperature ( $^{\circ}\text{F}$ )  
 $e$  = base of the natural logarithms (2.7183).

Now we can use eq 9 and the raw water temperature and TDS concentration data from Table 1 to predict the product water TDS concentration. Table 4 gives the predicted and measured product water TDS concentrations at the various raw water temperatures.

**Table 4. Measured and predicted TDS concentrations.**

Average raw water temp ( $^{\circ}\text{F}$ )	Raw water TDS conc (mg/L)	Product water TDS conc (mg/L)	
		Measured	Predicted
33.7	800	42	39.8
37.9	800	43	41.3
42.1	800	41	42.8
46.8	900	43	50.2
51.5	800	47	46.4
57.8	800	53	49.0
68.3	900	60	60.3

The standard deviation of the predicted product water TDS concentrations (more formally called the standard error of the estimate) is 3.4 mg/L. Two standard deviations on either side of the mean encompass 95.4% of the observations in a normal frequency distribution, so we can say that about 95% of the time the actual TDS concentration of the product water will be within 6.8 mg/L of the predicted concentration. For example, for a raw water temperature of 33.7 $^{\circ}\text{F}$  and a raw water TDS concentration of 800 mg/L, Table 4 shows a predicted product water concentration of 39.8 mg/L. Adding and subtracting 6.8 mg/L gives a range of 33.0 – 46.6 mg/L. This means that 95% of the time the actual TDS product water concentration from the ROWPU will be between 33.0 and 46.6 mg/L if the raw water temperature is 33.7 $^{\circ}\text{F}$  and the raw water TDS concentration is 800 mg/L.

## CONCLUSIONS

The equation developed in this report to predict TDS concentration in the product water from the 600-gph ROWPU is only preliminary. It was developed using a very limited range of raw water TDS concentrations (800–900 mg/L). Therefore it should not be used for raw water TDS concentrations outside of this range. Future work with the ROWPU will include using raw water with a high TDS concentration (such as seawater and brackish water) at different temperatures to determine product water flow rates and proportionality factors.

Once an equation is developed to accurately predict the TDS in the product water from the ROWPU over a broad range of raw water TDS concentrations and temperatures, studies will be conducted to determine the feasibility of developing similar equations for other dissolved chemi-

cals in the raw water. In this case particular attention will be paid to those chemicals that are included in the quality standards for treated water, such as magnesium and sulfate.

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